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Sedimentary chemofacies characterization by means of multivariate analysis

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Multivariate statistical analysis is applied to geochemical data from three sections forming part of the stratigraphic record of the Cerro Pelado Formation (Oligocene–Miocene), in the central region of the Falcón Basin, northwestern Venezuela. Our main goal is introducing and testing a statistical protocol for the identification of chemofacies in the studied sections. The first step involves data preparation and cleaning: selection of relevant components, convenient replacement of values below the detection limit and determination of outliers. Second, a biplot analysis allows us to infer geochemical processes that can be interpreted from a paleoenvironmental point of view: detrital association, redox-organic matter association and carbonatic association. Considering such geochemical associations, a constrained cluster analysis is then carried out to determine the chemofacies for each section. According to the compositional nature of geochemical data, all statistical analysis is conducted within a log-ratio analysis framework. In addition, robust statistical methods are considered for outlier detection and biplot representation in order to smooth the influence of potential outliers on the estimates.

1. Introduction

Geochemical signatures of clastic sedimentary rocks provide important sources of information that record different aspects of provenance, as well as tectonic, environmental and ecological evolution. Because hydraulic sorting, weathering and diagenesis can alter the geochemical composition of basin sediments, much emphasis has been placed on variations in the relatively immobile elements such as Cr, Co, Th, Y, Th, Zr, Ce, La, Sc and Ti. The low mobility of these elements during sedimentary processes enables better characterization of source rock compositions, paleo-climatic conditions and tectonic setting (Taylor and McLennan, 1985; Condie, 1993; Pearce et al., 1999; Spalletti et al., 2008).

Recent technological advances now enable the fast determination of major and trace element concentrations in a large number of samples from a sedimentary sequence. When a suite of elemental concentrations is evaluated in the context of the stratigraphic log, a chemostratigraphic study is accomplished, involving the application of major and trace elements for the characterization of the sedimentary sequence into geochemically distinct units (Winchester and Max, 1996; Das, 1997; Jarvis et al., 1998; Pearce et al., 1999; Reátegui et al., 2005); this tool can be very useful when applied to sequences with poor biostratigraphic control (Pearce et al., 1999). Other aspects revealed by chemostratigraphic studies are paleoproductivity, climatic changes and chemical cyclicity in processes involving basin sedimentation (Bellanca et al., 1996; Villamil, 1996; Dayong et al., 1999). Temporal variations in elemental abundances allow the characterization of sedimentary sequences by subdivision into chemical facies or chemofacies; these stratigraphic units exhibit a chemical signature, related to their environmental conditions of formation (Pearce et al., 1999; Reátegui et al., 2005).

Application of chemostratigraphic tools requires several components or attributes (e.g., Al, Si, Ca, Fe, Co, Ni, Cu and Zn) in a large set of rock samples collected in a stratigraphic order. As a result, multivariate data sets are obtained, so multivariate statistical methods are needed to investigate the orientation or trends of the underlying geochemical processes.

In this study, the geochemical data obtained are of a compositional nature, that is, they are vectors of non-negative values subjected to a constant-sum constraint. Namely, they are measured in units like wt.% (weight percent) or μg/g (micrograms per gram). This fact implies that

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relevant information is contained in the relative magnitudes, so statistical analysis must focus on the ratios between components (Aitchison, 1986). The suitability of the log-ratio approach for the analysis of data representing parts of a whole is broadly supported, as much from a theoretical viewpoint as from a practical one (see e.g., Weltje, 2002; von Eynatten, 2004; Pawlowsky-Glahn, 2005; Daunis-i-Estadella and Martín-Fernández, 2008; Barbera et al., 2009; Tolosana-Delgado and von Eynatten, 2009).

The aim of this work is to introduce a suitable statistical protocol for identifying chemofacies in sedimentary sequences, taking into account the compositional nature of the data. We evaluate this statistical approach on chemostratigraphic data of the Cerro Pelado Formation.

2. Study sequence — geological setting

The Cerro Pelado Formation lies in the Falcón Basin, northwestern Venezuela (Fig. 1), with a thickness greater than 1000 m. The Cerro Pelado Formation does not crop out in a continuous section. The two main sections sampled were at the El Troncón (bottom of the unit) and La Paloma (middle-upper part). A shorter section in the La Cuesta coal mine was also sampled (Fig. 1). This formation was deposited in an extensional basin associated with major strike-slip faults related to the passage of the Caribbean plate (Macellari, 1995; Audemard, 2001; Bezada et al., 2008). During its early history the basin (Oligocene and Early Miocene) subsided rapidly, and marine deep-water sedimentation eventually extended over most of it (Díaz de Gamero, 1977). The whole basin was subjected to intense deformation, resulting in numerous faulting and folding structures. The sedimentation of the Cerro Pelado Formation took place in the Urumaco Trough, in the western part of the basin. The unit was deposited during the Lower Miocene, in a regressive cycle (Hambalek et al., 1994), within a prograding deltaic system and its associated facies, including delta front, delta plains with interdistributary channels, swamps, and marshes. (Díaz de Gamero, 1989). In summary, the formation represents a transition from the marine environment of the underlying Agua Clara Formation to the very near-shore to coastal plain environment that prevailed when the overlying Querales Formation was deposited. The Cerro Pelado Formation consists mainly of lithic sandstones in beds up to 20 m thick, intercalated with shale and siltstone beds. Presumably the individual shale and siltstone beds have thicknesses of up to 2.7 m (Díaz de Gamero, 1977). The basal part of the unit is composed of grey to reddish-brown ferruginous sandstones with cross-bedding. The upper part of the unit is composed of bedded calcareous sandstones and calcareous shales containing coal beds up to 2 m thick (Díaz de Gamero and Linares, 1989). Shales are sometimes carbonaceous and contain grayish-blue limestone nodules; in addition, they contain fossils primarily typical of brackish waters (Hambalek et al., 1994). Sub-bituminous to bituminous coal beds are found in the middle and upper parts of the Cerro Pelado Formation; these were deposited in a marine sedimentary environment with lagoons and marshlands that developed due to delta advancement (González et al., 1985). The Cerro Pelado Formation is considered to be a probable reservoir rock in the petroleum system of Falcón Basin; several coal mines (Fig. 1) are present in its outcrop area (Ghosh et al., 1997).

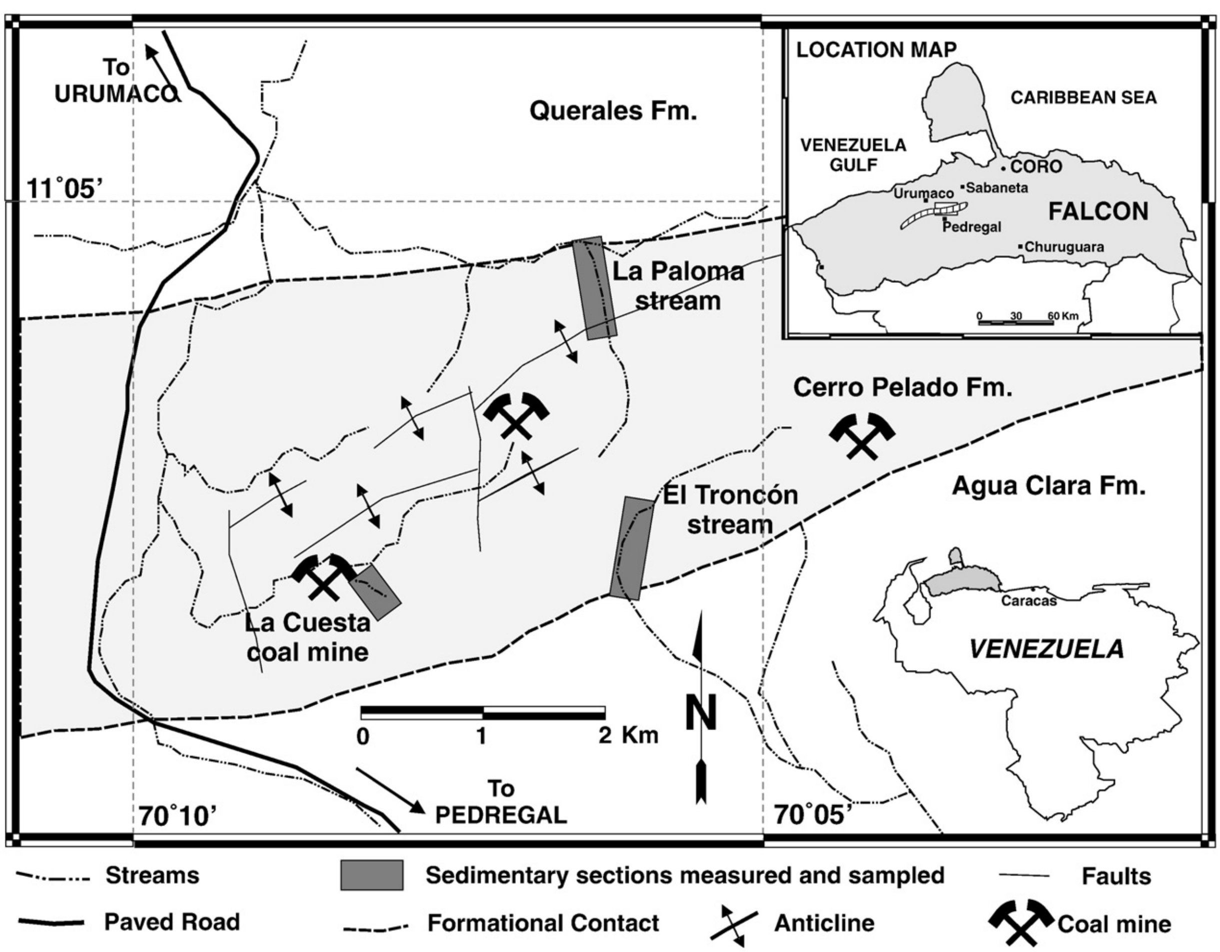

Fig. 1. Location map showing the three studied sections of the Cerro Pelado Formation (shaded area) in the Falcón Basin, northwestern Venezuela.